STAR Heavy Flavor Tracker (HFT)

Response to CD-1 Physics Questions

April 2010

1. Introduction

This report is written in response to the questions raised in the DOE document "Report on the Technical, Cost, Schedule and Management Review of the STAR Heavy Flavor Tracker". This review took place at Brookhaven National Laboratory in November 12-13, 2009, and is referred to here as the CD-1 review.

In the first part we describe the simulations that have been performed since the review and then address all the relevant questions.

In the Appendix we present simulations where we compare the significance of D^0 measurements when using HFT pixel technology versus PHENIX hybrid technology.

2. New HFT Simulations

The CD-1 questions emphasize the impact on physics of the HFT design parameters, especially in the low p_T region that is very sensitive to detector thickness. In this report we study the impact of increasing the mass of the first layer of the PXL detector from a value of 0.32 % of a radiation length (X_0) (thin configuration) to a value of 0.62 % X_0 (thick configuration), and of increasing the internal stability from 20 μm (design value) to 30 μm (CD-4 parameter). The thickness of the "thin" configuration is close to the present design parameter of 0.37% X_0, while the value for the "thick" configuration is close to what could be achieved by using Cu cables for the PXL readout and is also close to the CD-4 parameter for the thickness of the first pixel layer.

All simulations in this report were performed in the same environment as the ones included in the CDR and CD-1 presentations, i.e. the standard STAR simulation and reconstruction chain is used as well as the same HFT detector configuration (geometry). The HFT geometry used in all simulations (slightly different than the latest proposed design) comprises two layers of PIXEL detectors at 2.5 and 8 cm radius, one IST layer of 600 (r-ϕ) x 6000 (z) micron strip-lets at a radius of 14 cm and the existing SSD detector at 23 cm radius.

To summarize the additional simulation efforts after the CD-1 review:

- We ran new productions for thin/thick scenarios to more than quadruple our available statistics in the low p_T region.
- We performed multi-dimensional, cut-optimization studies for enhanced low p_T D^0 significance, resulting in a gain of efficiency of about a factor of two at low p_T.
- We re-evaluated our capability to measure the Λ_C /D^0 ratio.

3. CD-4 Parameters

We have changed two CD-4 parameters:

- The thickness of the first pixel layer was increased to <0.6% X_0. The effect of such a change is discussed in detail in this document.
- We have relaxed the parameter for internal alignment and stability from 20 μm to 30 μm. The effect of this increase over the current design parameter would be a reduction of significance for low p_T D^0 by about 10%. This result was obtained with our fast simulation program.

4. Answers to CD-1 questions

• Studies should be carried through to the final physics measurement, showing the degradation of the final physics significance if key requirements are not met:

–Give an explicit evaluation of what the loss in low-p_T efficiency does regarding the fundamental physics questions relating to flow and energy loss of heavy quarks in the hot-dense medium. Evaluate this loss in terms of current theoretical models and show whether these are well tested by the measurement above ~2 GeV/c or if the loss of statistics at lower p_T is a critical loss.

4.1. Thickness Studies

We have performed extensive simulations with the goal to evaluate the loss in D^0 signal sensitivity that would occur should we be forced to use a copper-kapton cable for the pixel ladders instead of a thinner aluminum-kapton cable. We have used two different configurations, the "thin" and the "thick" one, where the thin configuration is close to the actual pixel thickness with an Al cable and the thick one is close to a cable with Cu traces. The net 'physical' effect is a degradation of the single track DCA resolution by about 6 microns; from 32 (thin) to 38 (thick) microns for kaons of 750 MeV/c momentum.

Figure 1 shows the significance as a function of p_T for the thin and thick configurations. The difference between the open and filled symbols is in the generated shape of the spectrum. Filled symbols represent a flat p_T spectrum, while the open symbols correspond to a more realistic power-law p_T spectrum. The slight differences between the same (open/filled) symbols are consistent with statistical fluctuations. The circles show the signal significance for the standard thin-PXL configuration while the square symbols show the same for the thick-PXL case. The set of background-rejection cuts used to produce these curves is the same as the one used to produce the figures in our CDR and CD1 presentations.

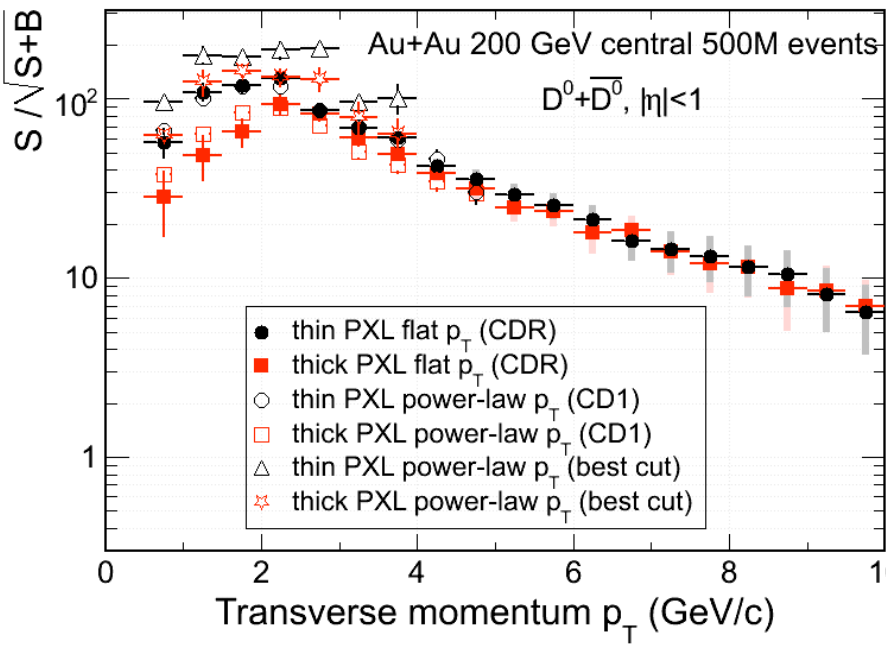

Figure 1: Signal significance as a function of p_T. Filled/open circles/squares show the change in significance due to thickness (thin/thick) for flat/realistic spectral shape. Open triangle/stars show a new result, the signal significance for thin/thick after a careful cut optimization was performed in the lower p_T region. The gray/pink error bands (prominent only at high p_T) are systematic uncertainties, mainly due to empty bins in the background.

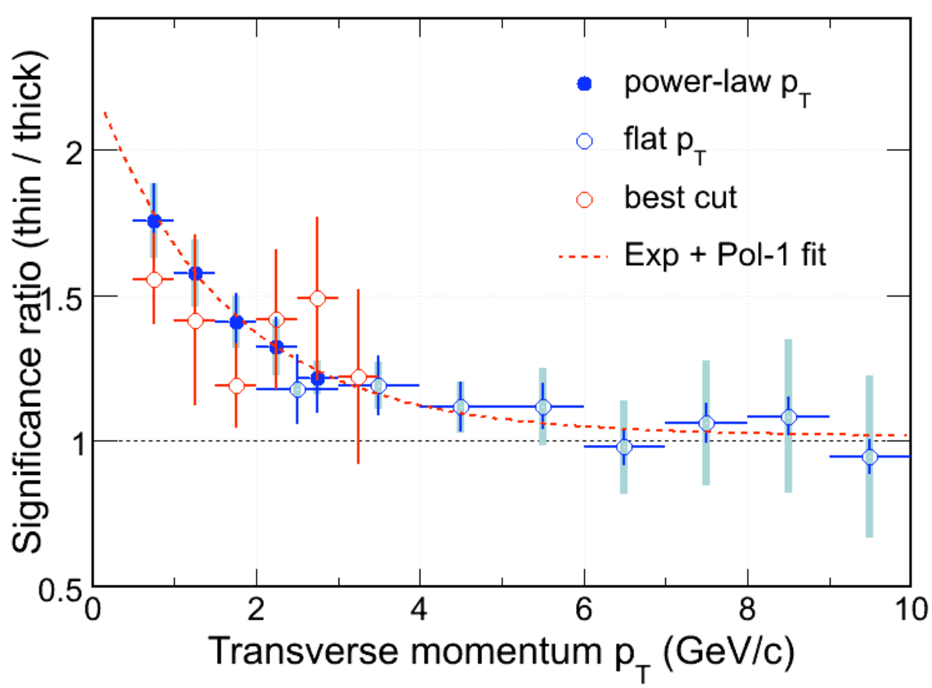

Figure 2: Impact of PXL thickness on signal significance as a function of p_T. The different symbols represent different p_T shapes and/or optimized cuts, as labeled.

Figure 2 shows the ratio of significance for the thin and the thick configuration as a function of p_T. For the thick configuration this shows a drop in significance between a factor of 1.5 and 2.0 in the important p_T region below 2 GeV/c. This result scaled to the actual increase in thickness, would imply a required increase in the number of acquired events of about a factor of 2 to 2.5 in order to keep the signal significance the same for the two cases.

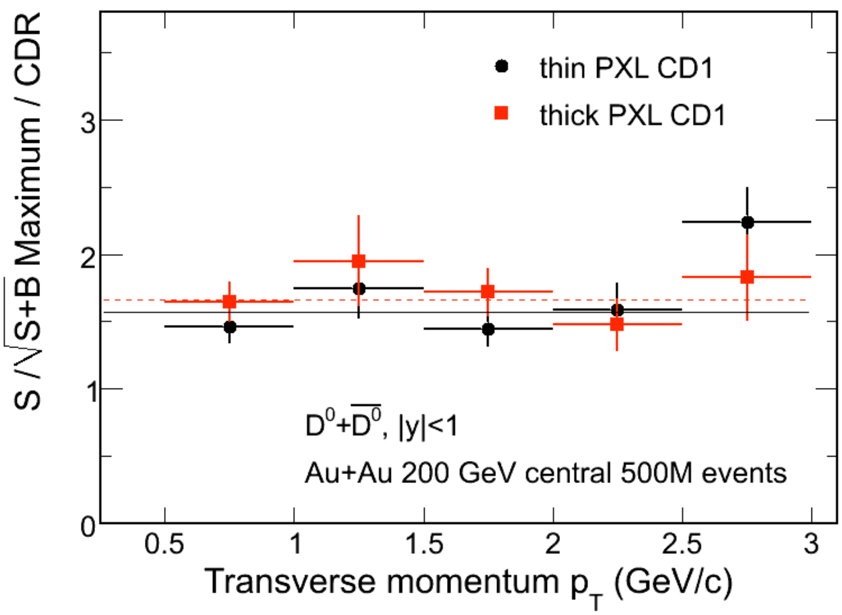

Figure 3: Signal significance gain as a function of p_T after cut optimization for thin (black symbols) and thick (red symbols).

Figure 1 also shows a new result, the signal significance for thin/thick but after a careful, multi-dimensional *cut optimization* was performed in the lower p_T region (open triangles and stars). The net gain from this optimization procedure (a factor of 1.5 – 2.0) is shown in Figure 3. We observe that the performance of the optimized cut set for the thick PXL (star symbols in Figure 1) is almost identical to the thin PXL (open/filled circles) if one uses the non-optimized cut set used in the CDR and CD1. **A potential increase in PXL thickness would not change the precision of low p_T values established in the CDR,**[i] since the loss in efficiency has been regained by tuning our low p_T cut parameters. As our analysis procedure is not yet fully optimized further gains in efficiency might be expected in the future.

In summary: The thick configuration would require to accumulate about a factor of two more events in order to achieve the same significance in the low p_T region as the thin configuration. However, a factor of 2 in significance has been gained by tuning the cuts. As a result, the significance shown in the CDR at low p_T can be achieved with the thick configuration.

4.2. R_{AA} and Heavy Flavor Suppression at High p_T

Energy loss is a high p_T phenomenon. We study it using R_{AA}, the ratio of AA to properly scaled pp p_T spectra. The relevant p_T region is above 4-5 GeV/c. As we can see in Figure 2 the impact of thickness (i.e. multiple scattering) in that region is negligible. We can, therefore, safely conclude that there is no thickness impact on this physics, for the thickness range under study.

4.3. Elliptic Flow

The low p_T region is important for studies of collectivity. Here we limit our discussion to v_2, for which the low p_T region and PXL thickness are most relevant. It is important to understand that flow is a hydrodynamic phenomenon. Data and hydro predictions agree up to about 1.5 GeV/c p_T, beyond which point data deviate dramatically from the hydro prediction. In Figure 4 we present the precision of measurement that can be achieved with the thin and the thick PIXEL configuration **within the first year** of data taking using estimation based on the optimized set of cuts. Also shown in the figure (red and green lines) are two different model calculations[ii] based on the coalescence assumption.[iii] Coalescence is an empirical observation deduced from v_2 systematics. In the same figure we also show the low p_T hydro prediction[iv] for the D^0 mass (blue line), plus our charged hadron results, as an overall reference (purple line). This clearly indicates that the high p_T end of the model calculations is not in agreement with existing data.

At low p_T we observe the typical hydro mass-scaling/splitting (e.g. the difference between the purple/data line (mostly pions) and the blue/hydro line) and at high p_T leveling off and scaling with the number of constituent quarks. The shape of v_2 at high p_T is not a hydro effect but is due to quark energy loss.[v] Reference ii has no predictive power at high p_T since it only assumes coalescence and does not include the effects of energy loss. The model uses light quark momentum distributions and for the heavy quark either non-interacting distributions (no flow) or completely thermalized distributions with transverse expansion (flow). In fact, if constituent quark scaling is to hold in the charm sector, the v_2 value at high p_T is determined only by the fact that the D^0 is a meson (not a baryon). In this scenario, the two theoretical curves must merge at high p_T. There is no realistic model on the market that would give quantitative guidance for v_2 values at low p_T and realistic predictions for v_2 at high p_T.

Therefore, a comprehensive comparison with theory predictions will not be possible, until we see a new description emerge. The comparison has to rely at present on systematic studies of v_2 scaling at low p_T as a function of particle mass. If the heavy quark flows, such systematics will show it. However, this further emphasizes the importance of testing coalescence in the charm sector.

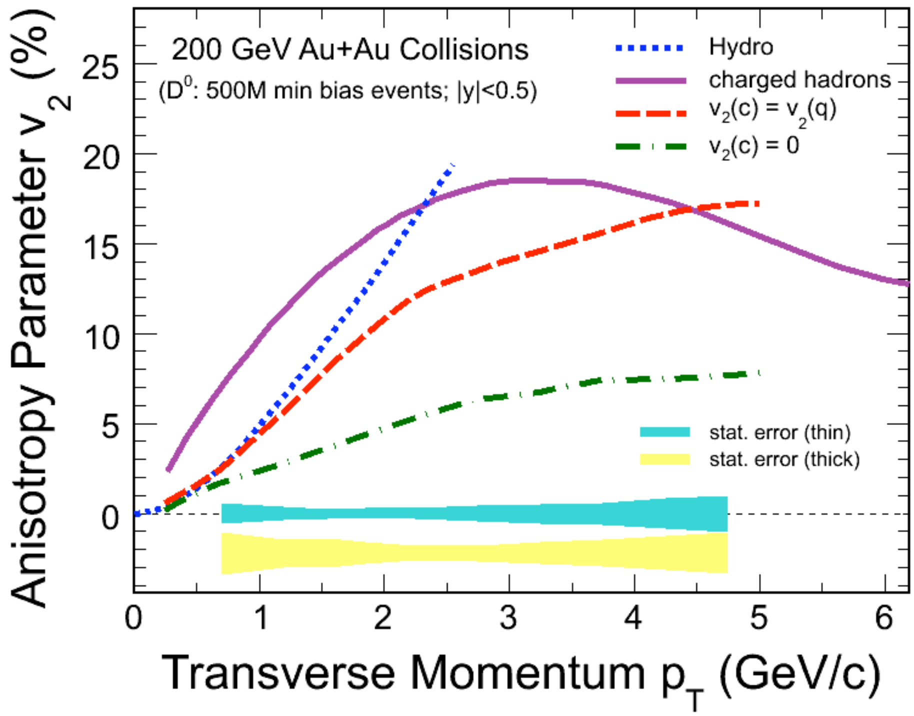

Figure 4: Elliptic flow (v2) vs pT in Au+Au collisions at 200 GeV. The purple curve shows the measured value for charged hadrons. The blue curve is a pure hydrodynamic calculation for the D^0 mass. The red and the green curves show calculations from Ref [ii] including effects of quark coalescence for the limiting cases that the charm quark flows like the light quarks and that the charm quark does not flow. The cyan band indicates the statistical error that can be achieved with 500 M minimum bias events for the thin detector configuration and the yellow band is for the thick configuration. In all error estimations we used the optimized cut set results.

The impact of thickness on model discrimination is shown as colored error bands in Figure 4. The statistical discrimination is based on 500 Million minimum bias Au+Au events, which correspond, in a pessimistic scenario of machine/detector duty factors, to a RHIC-year's run worth of data. We see that **both thin and thick** configurations will allow for a **first year statement** about

- The overall, experimentally determined, flow of identified D^0s as a function of p_T, starting at about 0.8 GeV/c.
- The comparison of the magnitude of D^0 flow with the two extreme coalescence scenarios (red and green lines).
- Both configurations will be able to discriminate between the two extreme model assumptions.
- The thin configuration will allow for some first year discrimination between the hydro and full-flow coalescence scenario (blue and red lines in the figure), but the thick PXL configuration will probably need another year's run to make this distinction.

Besides v_2 scaling, the Λ_C to D^0 cross-section ratio represents an ideal test of coalescence. Later in this document (Section 4.4) we summarize the capability of the HFT to determine a baryon to meson ratio in the charm sector as well as the thickness impact on this measurement.

- **Compare the significance of planned charm and beauty measurement to be done with the HFT to similar measurements expected from the upgraded PHENIX detector. Comment on how significant an advance in theoretical understanding of energy loss and flow for the hot-dense medium the HFT would provide compared to the earlier anticipated PHENIX measurements**

Historically (e.g. at Fermilab) the heavy flavor physics program became much stronger and sharper after high precision silicon detectors were added to the experiments.[vi] It is obvious that PHENIX will perform important charm and beauty measurements before the HFT becomes operational. The emphasis of the PHENIX measurements is on identifying electrons from charm and beauty decays. Such measurements have limitations that can be overcome by topological reconstruction in the case of the HFT. PHENIX has not shown simulations that would establish the capability to do topological reconstruction of D-mesons.[vii] Therefore we will attempt a qualitative comparison of what can be done with the HFT and PHENIX with respect to the physics extracted from the measurement of the electrons from semi-leptonic D- and B-meson decays. It is beyond the scope of this report to speculate about the PHENIX capability to perform topological reconstruction. In the Appendix we compare the sensitivity for topological reconstruction for HFT pixel technology and for PHENIX hybrid technology.

PHENIX will measure the spectra of non-photonic electrons from charm and beauty decays. The new information that the HYBRID vertex detectors will provide is the electron impact parameter (DCA) from the event vertex. The reconstruction technique is based on applying DCA cuts to reject background and then fit the yields in various p_T bins. This will result in a spectrum of the sum of D and B decays. Taking the difference in $c\tau$ for charm and bottom into account, D and B separation can be achieved through unfolding. The unfolding process is complicated by the fact that the different D states have quite different $c\tau$ values, where for example the D^+ $c\tau$ is very close to the B $c\tau$. Unfolding has to make assumptions about the production ratio for the individual D states. For p+p this is well known. However, in case the production ratio is modified in heavy ion reactions, unfolding becomes unreliable. This potentially large uncertainty can be mitigated in the STAR non-photonic electron measurement because STAR will directly measure D^0, D^+, and D^s production.

PHENIX will perform a measurement of the R_{AA} for electrons from D and B decay as a function of p_T. Due to momentum smearing from the decay process, the parent p_T

cannot be determined, thus preventing a precision measurement of R_{AA} for heavy flavor hadrons as a function of p_T. This might be very important for a precision comparison with model calculations to determine the mechanism of energy loss.

PHENIX also will determine v_2 of non-photonic electrons. This measurement cannot contribute to the question of thermalization. The parent p_T is not determined to better than 3 GeV. We have argued above that only a measurement at low p_T (< 2.5 GeV/c) might be able to answer this important question.

We believe the following statements to be correct:

- The theory development in the area of energy loss is progressing rapidly and it is not obvious what it will be in a few years. It is, however, safe to say that quality data are the requirement for theory progress.
- All measurements by STAR based on topological reconstruction are original and without competition at RHIC.
- PHENIX and STAR will both measure charm/beauty production cross sections from the electron spectra.

D and B production can be separated also by multi-particle correlations.[viii] Neither PHENIX nor STAR has shown this capability in simulations. Since 2π acceptance is important for two- and multi-particle correlations, it can be assumed that STAR has advantages for this particular measurement.

In summary, a measurement of non-photonic electrons has a limited reach. The full potential of heavy flavor physics in heavy ion collisions can only be reached through full topological reconstruction.

4.4. Update on Λ_C Simulations

Since the CDR we have increased statistics of our simulations, to allow for better optimization of cuts also in the Λ_C analysis. Despite these improvements, estimated errors in the 2-3 and 3-4 GeV/c p_T bins haven't changed significantly, showing the robustness of our CDR estimates.

Figure 5 shows the expected statistical errors of the ratio of Λ_C to D^0 production for different assumptions about the production mechanism. A significant improvement with respect to the uncertainty reported in the CDR was achieved in the 4-5 GeV/c p_T bin, where we didn't require full identification of daughter particles, resulting in improvements in Λ_C reconstruction efficiency and (as background is modest in this higher p_T bin) increased Λ_C signal significance.

Note that in the figure, the discrimination should be made between estimated errors and the 2 scenarios of Λ_C /D^0 ratio - not between the two sets of estimated errors. The significance of this discrimination is in the range 2-4 sigma in the case of an enhanced ratio and about 4-6 sigma in the extreme case of no enhancement.

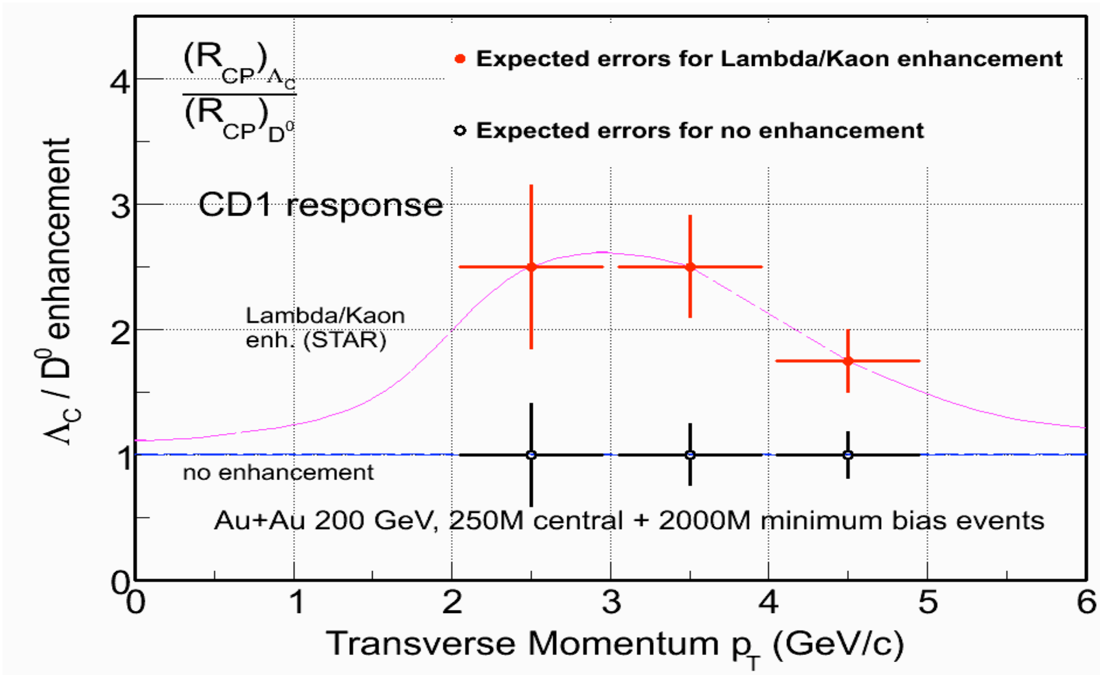

Figure 5: Expected statistical errors of the ratio of Λ_C to D^0 production for different assumptions about the production mechanism, performed for the "thin" detector configuration.

Similar simulations and analysis of simulated data were conducted for the "thick" detector configuration. Obviously, the error bars are larger, close to a factor of two (for the same amount of events). Only the middle bin (3 to 4 GeV/c p_T) shows non-overlapping error bars in that case.

In summary, we will be able to make a significant measurement of the Λ_C /D^0 ratio with the thin HFT configuration. This measurement will become much harder with the thick detector configuration.

Appendix:

We have also performed simulations of the significance of D^0 spectra for the case where we use the PHENIX hybrid technology (ie. pixel dimensions) instead of the HFT pixel technology. We did not change the detector thickness or the geometrical acceptance, but we used the thick PXL configuration since it is the closest available. Figure 6 shows the ratio of significance for pixel versus hybrid technology as a function of p_T. For a given number of events the significance of a HFT measurement is about a factor of 10 better. This means that in order to achieve the same significance as STAR, PHENIX would have to acquire a factor of a hundred more events. Important factors, like partial (PHENIX) acceptance, have not been factored into this rough estimate.

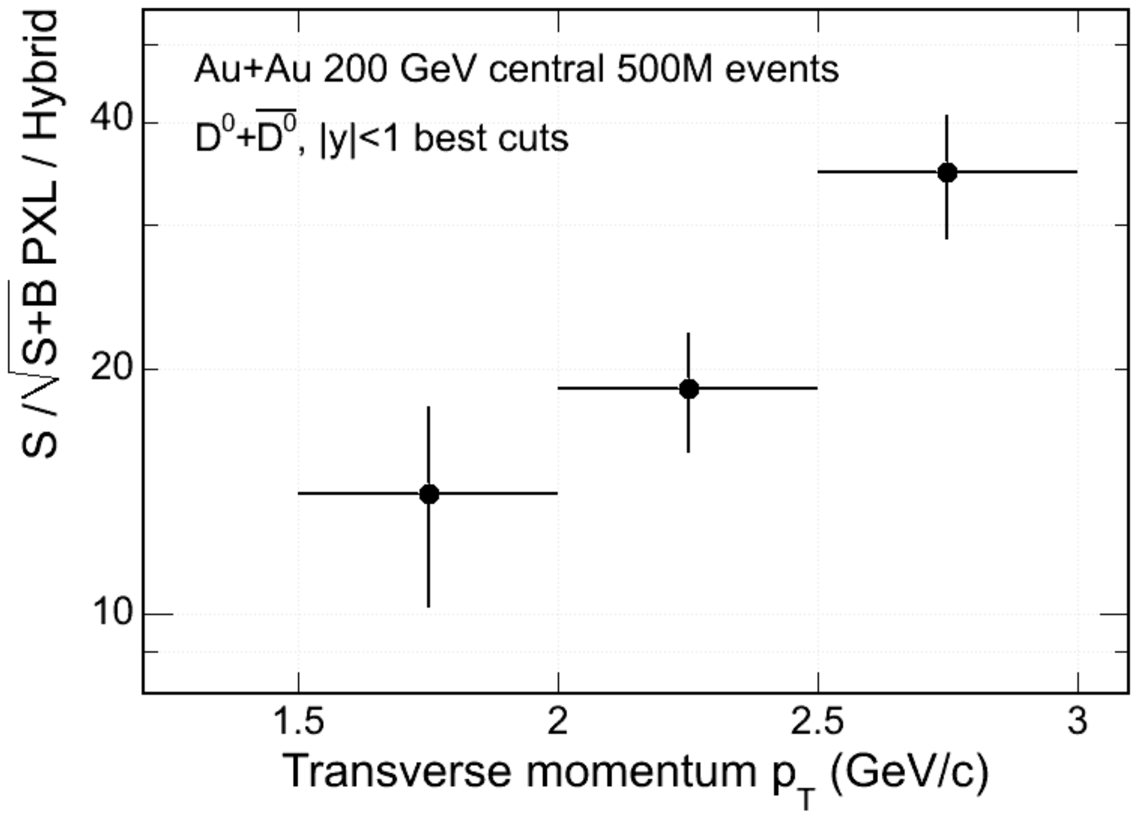

Figure 6: Gain in significance by using HFT PXL technology versus PHENIX hybrid technology.

References:

[i] http://www4.rcf.bnl.gov/~videbaks/hft/cd1/HFT_CDR_V26.pdf

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